THE BALLOON-BORNE LARGE APERTURE SUB-MILLIMETRE TELESCOPE

Douglas Scott[1]
and the BLAST Team:
Peter Ade[2], **Jamie Bock**[3], **Paolo DeBernardis**[4], **Mark Devlin**[5], **Matt Griffin**[2], **Josh Gundersen**[6], **Mark Halpern**[1], **David Hughes**[7], **Jeff Klein**[5], **Silvia Masi**[4], **Phil Mauskopf**[8], **Barth Netterfield**[9], **Luca Olmi**[10], **Lyman Page**[11], **Greg Tucker**[12]

[1]Dept. of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, B.C. V6T1Z1, Canada
[2]Queen Mary and Westfield College, London, UK
[3]Jet Propulsion Laboratory, Pasadena, CA, USA
[4]University of Rome, Rome, Italy
[5]University of Pennsylvania, Philadelphia, PA, USA
[6]University of Miami, Coral Gables, FL, USA
[7]INAOE, Puebla, Mexico
[8]Cardiff University, Cardiff, UK
[9]University of Toronto, Toronto, ON, Canada
[10]University of Massachusetts, Amherst, MA, USA
[11]Princeton University, Princeton, NJ, USA
[12]Brown University, Providence, RI, USA

Abstract

The Balloon-borne Large-Aperture Sub-millimetre Telescope (BLAST) will operate on a Long Duration Balloon platform with large format bolometer arrays at 250, 350 and 500 μm, initially using a 2.0 m mirror, with plans to increase to 2.5 m. BLAST is a collaboration between scientists in the USA, Canada, UK, Italy and Mexico. Funding has been approved and it is now in its building phase. The test flight is scheduled for 2002, with the first long duration flight the following year. The scientific goals are to learn about the nature of distant extragalactic star forming galaxies and cold pre-stellar sources by making deep maps both at high and low galactic latitudes. BLAST will be useful for planning *Herschel* key projects which use SPIRE.

Key words: Balloons – Submillimeter – Dust – Cosmology: observations – Galaxies: evolution

1. Introduction

The far-IR background was first discovered in the *COBE* data 5 years ago (Puget et al. 1996), and has since been estimated at several wavelengths in the 100 μm to 1 mm range (Fixsen et al. 1998; Hauser et al. 1998; Lagache et al. 1999). As shown in Fig. 1, the Far-IR Background (FIB) represents the most significant energy density of photons after the CMB, and is roughly a factor of two larger than the optical/near-IR background (although this is still debated). The FIB peaks around 100 μm, and appears to be wider than the CMB (indicating perhaps that the sources come from a range of redshifts). Unlike for the x-ray background, we only had to wait a year or two before a significant fraction of the FIB had been resolved.

Several surveys with the SCUBA instrument on the James Clerk Maxwell Telescope found a great many more sources than expected in no evolution models (e.g. Smail, Ivison & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Lilly et al. 1999; Chapman et al. 2001; Borys et al. 2000). The most sensitive SCUBA band at 850 μm favours high redshift dusty galaxies compared with those providing most of the FIB. Or in other words, the background at these wavelengths is about a factor of 30 below the value at the peak. Hence SCUBA does not tell us directly about the bulk of the galaxies responsible for the FIB. However, information about sources at the peak itself has also recently came from surveys with ISOPHOT on the *ISO* satellite. The FIRBACK survey, for example, has provided deep maps over several square degrees at 170 μm which resolve about 10% of the background (Puget et al. 1999; Scott et al. 2000a; Dole et al. 2001).

Many questions remain however: What are the redshifts, star-formation rates and morphologies of these FIRBACK galaxies? What makes up the other 90% of the far-IR background? How are these objects related to the SCUBA-bright sources? Are they the higher redshift equivalents of local luminous and ultra-luminous infrared galaxies? Is merging involved? Are they related to AGN activity? In order to answer such questions we need to obtain data at a wide range of different wavelengths, with the smallest possible beam-sizes, to aid comparison between data sets. A crucial part of this puzzle is deep mapping at far-IR/sub-mm wavelengths which are near the peak of the background.

This is one of the main motivations behind BLAST (Devlin et al. 2000). At balloon altitudes the atmosphere is essentially transparent at 250 μm (see Fig. 2), while those wavelengths are impossible from the ground. At 350 μm observations from the best observatory sites are possible, but extremely challenging. Working in the atmospheric

Proc. of *'The Promise of FIRST'* symposium, 12–15 December 2000, Toledo, Spain (G.L. Pilbratt, J. Cernicharo, A.M. Heras,

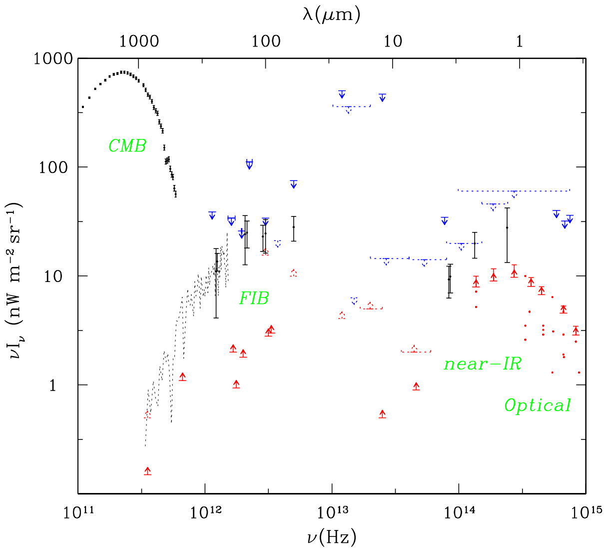

Figure 1. Extragalactic background radiation measurements and constraints from the cm-wave through to the optical region. The infrared background is beginning to be traced out over a wide wavelength range, and has a peak near 100 μm. Here points with error bars represent measurements, while arrows are upper or lower limits, and dashed lines show model dependent limits. Earlier plots with extensive references appear in Scott et al. (2000b) and Halpern & Scott (2000).

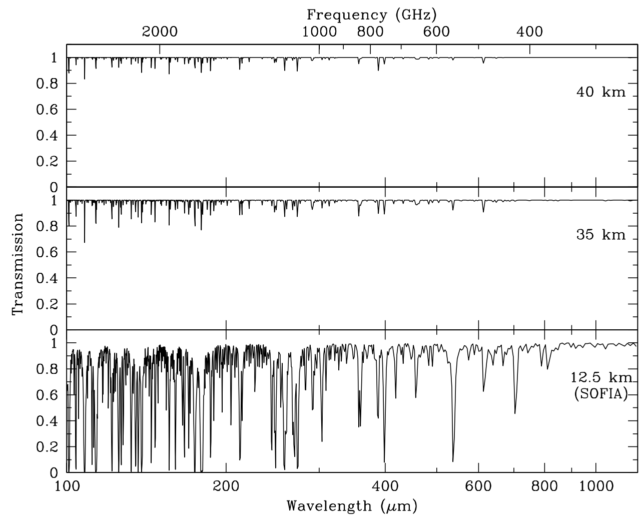

Figure 2. Atmospheric transmission at three different sub-orbital altitudes. At typical ballooning altitudes the atmosphere is essentially transparent across this whole wavelength range. This should be contrasted with SOFIA altitudes and even the best high-altitude observatories (not shown), where things are considerably worse.

window at 450 μm from sites like Mauna Kea is considerably easier, but even there the atmosphere typically makes the data 10 times noisier than at 850 μm. BLAST will also have a channel at 500 μm, which will be important for connecting to the ground-based sub-mm observations. But for BLAST, pushing to the shorter wavelengths enables the beam-size to be smaller. By flying a mirror of diameter $\gtrsim 2$ m (significantly larger than flown in most CMB balloon projects, for example), BLAST is able to recover a beam-size which is similar to that of ground-based sub-mm telescopes.

By carrying out deep surveys at high and low galactic latitudes, BLAST will be able to address many related science goals, including:

1. sub-mm continuum of solar system objects (planets, asteroids, ...);
2. study of cool dust in the ISM (pre-stellar objects, mass function of clumps, ...);
3. nearby galaxies (distribution of cool dust, relation to star formation, ...);
4. distant galaxies (number counts, resolving the far-IR background, star formation history, ...);
5. correlations (clustering of far-IR galaxies, bias, merging, ...);

2. Technical description

BLAST is the Balloon-borne Large Aperture Sub-millimetre Telescope, designed to map parts of the sky at sub-mm wavelengths which are essentially impossible from the ground. BLAST is a collaboration between 16 scientists at a dozen institutions in 5 countries, with PI Mark Devlin at the University of Pennsylvania.

BLAST (see Fig. 3) will initially use an available 2 m diameter primary, with plans to upgrade to a larger mirror for later flights. Detectors will consist of an array of 280 spider-web bolometers at three different wavelengths, with most of the bolometers being at the shortest wavelength, and the entire field of view being 6.5×13 arcminutes. BLAST uses the same array structure as the *Herschel* SPIRE instrument. The central wavelengths will be 250 μm, 350 μm and 500 μm, with beam-widths of about 30, 41 and 59 arcseconds, respectively. In a 6 hour map of 1 square degree BLAST will have a 1σ sensitivity of about 15 mJy at each of the three wavelengths (see Table 1 for detailed parameters).

Much of the emphasis for the BLAST team has been a fast delivery of Science, and so the schedule calls for the first flight (from North America) in 2002, with the first long-duration flight in 2003.

3. BLAST Surveys

3.1. Deep cosmological surveys

BLAST will carry out both Galactic and extra-galactic surveys. For a 6 hour test flight we can map a region of

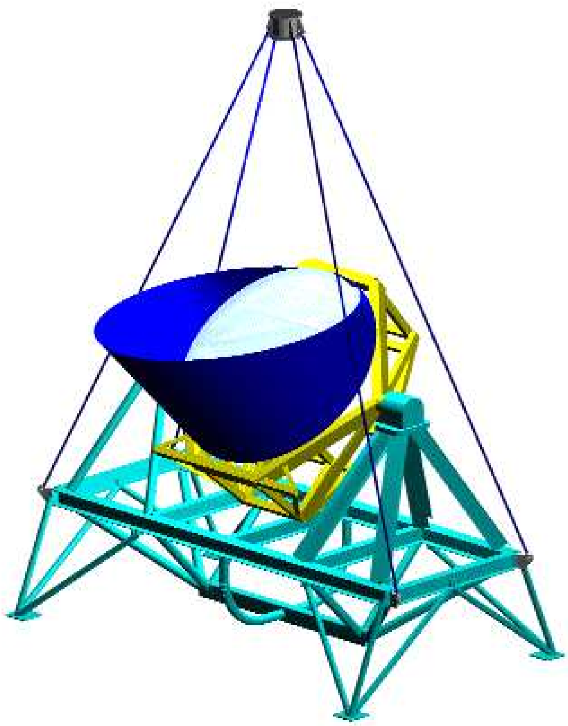

Figure 3. The BLAST telescope and balloon gondola design is shown here, with sun shields and ground shields removed. The alt-az pointing system will have an absolute accuracy of better than $10''$, limited by gyroscope and daylight star-sensor performance.

Table 1. Experimental parameters for BLAST.

Central wavelength	$250\,\mu$m	$350\,\mu$m	$500\,\mu$m
Number of pixels	149	88	43
Beam FWHM	$30''$	$41''$	$59''$
NEFD (mJy.$\sqrt{\rm s}$)	236	241	239
$\Delta S_\nu[1\sigma$,1 hr,1 deg$^2]$ (mJy)	38	36	36

$0.55\,\mathrm{deg}^2$ to the confusion limit. This will be centred on one of the fields which have been well studied at other wavelengths, e.g. the Lockman Hole, HDF region or one of the ELAIS ISO fields. With rms sensitivity of about 10 mJy at each wavelength, we might detect 150 sources at $> 5\sigma$. Combination of BLAST fluxes with those from other instruments and facilities (e.g. VLA, SCUBA, BOLOCAM, optical, *CHANDRA*, *XMM*) will allow the properties of the sub-mm luminous galaxies to be studied across the full electromagnetic spectrum. A long-duration flight allows for a much larger region of tens of square degrees to be mapped down to the confusion limit, and about 1500 galaxies should be well detected. Coordinating this with the *SIRTF* SWIRE Legacy survey, for example, would make scientific sense.

3.2. Galactic Plane Surveys

In the plane of the Milky Way BLAST will map a modestly-sized bright region during the test flight. A long-duration flight would allow for, say, a $5° \times 10°$ map of the Galactic Centre region, where there is already extensive multi-wavelength data (e.g.Pierce-Price et al. 2000). Combination of the BLAST map with data from SCUBA, *MSX*, *IRAS*, *ISO*, the Canadian Galactic Plane Survey, etc. would allow many different galactic science investigations:

– studies of individual clouds and complexes;
– profiles and other properties of pre-stellar cores;
– mass functions of star-forming clumps;
– dus-to-gas ratio variations;
– studies of turbulence;
– correlations between $T_{\rm dust}$ and emissivity;
– grain properties.

3.3. Statistics of Maps

The traditional quantity derived from surveys is an estimate of the counts of well-detected sources, $N(>S)$. This is the mainstay of extragalactic studies in the far-IR/sub-mm, and a similar approach is used in many Galactic studies also. A great deal of theoretical modelling of galaxy counts has been carried out (e.g. Guiderdoni et al. 1998; Pearson & Rowan-Robinson 1996; Franceschini et al. 1994; Tan, Silk & Balland 1999; Takeuchi et al. 2001; Malkan & Stecker 2001). Detailed number counts can constrain the evolution of the various populations of galaxies. Here multi-wavelength studies (e.g. BLAST + SCUBA + . . .) constrain the models much more effectively, and ultimately the models are really pinned down when redshift data become available.

Number counts are clearly not the only statistic obtainable from a map. This is particularly clear for dust maps at low galactic latitudes, where there is structure on all scales, and the most physically motivated statistical descriptors have yet to be firmly established. The same is at least partly true for extragalactic maps, but there it is expected that the bulk of the information *will* be contained in one- and two-point statistics. One point statistics, i.e. looking at histograms of pixel intensities, allow an estimate of source counts below the individual detection limit. Usually referred to as $P(D)$ analysis in radio and x-ray astronomy, this has been applied to SCUBA data by Hughes et al. (1998), for example.

Two-point correlation statistics have been used to look at faint sources producing fluctuations in the far-IR background (Lagache et al. 2000) and in SCUBA maps (Peacock et al. 2000). However, so far it is only the Poisson fluctuations due to sources that are undetected individually that have been measured – correlations from cluster-

ing of the sources has proved ellusive. This is another direction in which BLAST could make substantial progress. The amplitude of clustering of sub-mm bright galaxies is entirely unknown at this point. Presumably they will be quite highly biased, making them strongly clustered. But if they come from a wide range of redshifts their angular clustering will be partially washed out. Some estimates have been made (e.g. Scott & White 1999; Haiman & Knox 2000; Gaztañaga & Hughes 2001), with the most thorough theoretical investigation so far by Knox et al. (2001). These estimates indicate that clustering of the galaxies which comprise the FIB can dominate over shot-noise at scales above about 10 arcminutes. Measuring such correlations in the maps would provide additional constraints on galaxy evolution models, bias, clustering, etc. In general this is challenging, since it requires making maps with no systematic effects at the largest scales. However, this is certainly feasible for BLAST.

4. Conclusions

Clearly the SPIRE instrument on *Herschel* will have extraordinary capabilities for mapping at sub-millimetre wavelengths. In the meantime, however, it is possible to get more modest amounts of data much more cheaply and much more quickly. The data produced by BLAST should be very useful in planning ambitious surveys with SPIRE.

Acknowledgements

DS would like to thank the organisers of the 'Promise of *FIRST*' Symposium for a fun and intersting meeting.

References

Barger A.J., Cowie L.L., Sanders D.B., Taniguchi Y. 1998, Nature, 394, 248 [astro-ph/9806317]

Borys C., Chapman S., Halpern M., Scott D., 2000, Deep Millimeter Surveys, eds. J. Lowenthal and D. Hughes, in press, astro-ph/0009143

Chapman S.C., et al. 2001, MNRAS, in press, astro-ph/9909092

Devlin M., et al. 2000, 'Deep Millimeter Surveys', in press, astro-ph/0012327

Dole H., et al. 2001, A&A, in press

Fixsen D.J., Dwek E., Mather J.C., Bennett C.L., Shafer R.A. 1998, ApJ, 508, 123 [astro-ph/9803021]

Franceschini A., Andreani P., Danese L. 1998, MNRAS, 296, 709

Gaztañaga E., Hughes D.H. 2001, Deep millimeter surveys, eds. J. Lowenthal and D. Hughes, World Scientific, in press [astro-ph/0103127]

Guiderdoni B., Hivon E., Bouchet F., Maffei B. 1998, MNRAS, 295, 877 [astro-ph/9710340]

Halpern M., Scott D., 1999, Microwave Foregrounds, eds. A. de Oliveira-Costa, M. Tegmark, ASP, San Francisco, p. 283 [astro-ph/9904188]

Hauser M.G., et al. 1998, ApJ, 508, 25

Hughes D.H., et al. 1998, Nature, 394, 241

Haiman Z., Knox L. 2000, ApJ, 530, 124

Knox L., Cooray A., Eisenstein D., Haiman Z. 2001, ApJ, in press [astro-ph/0009151]

Lagache G., Abergel A, Boulanger F., Désert F. X., Puget J.-L. 1999, A&A, 344, 322 [astro-ph/9901059]

Lagache G., et al. 2000, ISO Surveys of a Dusty Universe, in press, astro-ph/0002284

Lilly S.J., et al. 1999, ApJ, 518, 641 [astro-ph/9901147]

Malkan M.A., Stecker F.W. 2001, ApJ, in press, astro-ph/0009500

Peacock J.A. et al. 2000, MNRAS, 318, 535 [astro-ph/9912231]

Pearson C., Rowan-Robinson M. 1996, MNRAS, 283, 174

Pierce-Price D., et al. 2000, ApJL, in press [astro-ph/0010236]

Puget J.-L., et al. 1996, A&A, 308, L5

Puget J.-L., et al. 1999, A&A, 345, 29 [astro-ph/9812039]

Scott D., et al. 2000a, A&A, 357, L5 [astro-ph/9910428]

Scott D., Silk J., Kolb E., Turner M.S., 2000b, Chapter 26 in Allen's Astrophysical Quantities, ed. A.N. Cox, 1999, Springer-Verlag, New York

Scott D., White M. 1999, A&A, 346, 1 [astro-ph/9808003]

Smail I., Ivison R.J., Blain A.W. 1997, ApJ, 490, L5

Takeuchi T.T., et al. 2001, PASJ, in press, astro-ph/0009460

Tan J.C., Silk J., Balland C. 1999, ApJ, 522, 579